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Helium Tracer Tests for Assessing Air Recovery and Air Distribution During In Situ Air Sparging

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13. ABSTRACT *(Maximum 200 words)*

Helium tracer tests are used as an alternative to soil-gas pressure measurements to assess the effectiveness of soil vapor extraction (SVE) systems for capturing contaminant vapors liberated by in situ air sparging (IAS). The tracer approach is simple to conduct and provides more direct and reliable measures than the soil-gas pressure approach. The tracer test described here can be used to both determine SVE system capture efficiency and to evaluate air distribution during IAS pilot tests. The tests can also be conducted on operating, full-scale systems to confirm system performance. In addition, tests can be easily repeated, which allows system parameters to be modified and the impact of those modifications to be quickly assessed. Whether used alone or in conjunction with other diagnostic tools, helium tracer tests provide an important measure of IAS system performance.

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Helium Tracer Tests for Assessing Air Recovery and Air Distribution During In Situ Air Sparging

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1.0 BACKGROUND

Uncontrolled vapor migration during in situ air sparging (IAS) can pose a risk to nearby receptors. In those cases where a risk pathway is present, soil vapor extraction (SVE) systems are frequently installed to mitigate that risk. In general, it has been assumed that vadose zone pressure data can be used to assess the performance of the SVE system. The basic idea is that if the SVE system can maintain sub-ambient pressure throughout the sparge zone, all of the sparge air will be captured. However, if strata are present below the water table, air can migrate away from the IAS system below the water table. If there is substantial lateral migration below the water table, then the sparge air can migrate beyond the reach of the SVE system before it reaches the water table, in which case pressure measurements alone may not correctly assess SVE performance.

In order to be more protective, a simple diagnostic tool should be used to more-directly and robustly measure SVE performance for capturing IAS air. One approach is to use inert gas tracer tests to assess the effectiveness of the SVE system for capturing the IAS air (Johnson et al., 1996; Johnson et al., 1997).

The same tracer test can also be used to assess the appearance of tracer gas in the deep vadose zone in order to identify where IAS air exits the water table. This can provide important insights into the distribution of air in the groundwater around the IAS well as well as provide guidance for spacing wells if the Site-Specific Design Approach is used. The additional measurements required to evaluate the air distribution can be easily incorporated into the tracer test used to assess the SVE system.

This manuscript provides a description of the methods for conducting the tracer test to both determine SVE system efficiency and to evaluate air distribution during IAS. Examples of the implementation of the tracer test are discussed to illustrate the evaluation of the data.

2.0 EXPERIMENTAL METHODS

Described in the following sections are the methods for assessing recovery of IAS air by and SVE system and for evaluating IAS air distribution at the water table. One of the strengths of the tracer test is that it can be easily repeated, usually with delays of only a few hours or so between them. This allows the effects of process changes (e.g., distribution of air flow from various wells) to be quickly assessed.

Helium is the most common tracer gas used, since it is relatively inexpensive, readily available, and analytical instrumentation is available for field use. Typical field instrumentation is a Marks Product model no. ??? helium detector. The detector can detect helium concentrations from 0.1% to 100%. It is factory-calibrated, so cannot be calibrated in the field, but checks should be made with helium standards to verify the instrument is operating properly. Typically, vapor samples must be collected in Tedlar™ bags or canisters. The helium detector is then attached directly to the sample container for measurement. A minimum of ? mL of sample is necessary. Alternatively, the helium detector can be modified to sample continuously Continuous sampling is very convenient when measuring SVE off-gas where a continuous flow stream is available.

2.1 Tracer Test to Assess Recovery of IAS Air by an SVE system

The tracer recovery tests described here are designed to be conducted on an IAS system that is already operating and after the air flow patterns have stabilized. It can be conducted as part of a pilot test, or during full-scale operation. To be most useful, the IAS and SVE wells should be co-located. The test is very simple to conduct and interpret. Basically, an inert tracer (usually helium) is introduced into the IAS air at a constant, known rate and the concentration of tracer is monitored in the SVE off-gas air (Figure 1a). After some period of time (e.g., an hour or less for many systems), the concentration of the tracer in the off-gas begins to rise. It continues to rise and eventually reaches a stable plateau.

The percent of the IAS air that is captured can be calculated by multiplying the SVE flow rate by the fraction of helium in the SVE air once the concentration has stabilized and dividing that number by the tracer injection rate as shown below.

$$\%\text{Recovery} = \frac{\text{SVE flowrate}}{\text{Trace injection rate}} \times \%\text{ tracer in off-gas} \times 100 \qquad (1)$$

A more robust field technique for calculating recovery is to first measure the "100% recovery concentration" in the SVE off-gas by directly injecting the helium into the SVE manifold at the same rate used for IAS injection (care must be taken to insure that the flow is the same in both cases since the back-pressures for the two systems are significantly different.) In this case the percent recovery of the IAS air by the SVE system is simply the helium concentration measured in the SVE off-gas divided by the "100% recovery concentration".

If helium is used as the tracer, the injection concentration should be kept below 10% by volume to avoid buoyancy effects in the vadose zone. To insure consistent helium flow under conditions of varying back-pressure, a calibrated direct-reading flow meter should be used along with a pressure gauge and a metering valve to provide a consistent, high back-pressure at the flow meter (Figure 1a).

The tracer recovery test is designed as a "red flag" for IAS system performance. If the recovery of helium is low, then it is possible that air (and helium) is being trapped below the water table beneath lower-permeability strata (Figure 1b) and may be moving laterally beyond the reach of the SVE system. In some cases it is possible that no helium will return to the well due to the presence of continuous layers. The presence of these layers should also be detectable by monitoring groundwater pressure during IAS startup and shutdown (Johnson et al., 2000). Therefore, it is recommended that the helium recovery test be conducted in conjunction with groundwater pressure measurements.

If helium recovery is high (e.g. >80%) then the SVE system is performing well with regard to IAS air recovery and lateral migration of vapors is unlikely to be a problem. Additional information regarding the distribution of air based on the recovery tests can be obtained if vadose zone transport times are calibrated using a procedure similar to that presented by P.C. Johnson et al. (this issue)

2.2 Tracer Test Procedure to Determine the Distribution of IAS Air at the Water Table without an SVE System (or with Co-Located SVE and IAS Wells)

If a number of discrete-depth vadose zone monitoring points (e.g., 6 to 12) are placed near the water table and distributed around the injection well, the tracer test described above can also be used to assess IAS air distribution at the water table. In the absence of an SVE system (or with it turned off), the monitoring points are sampled every few minutes for the appearance of

tracer. The presence of tracer at locations in the deep vadose zone within approximately 15 to 20 minutes of tracer startup indicates that IAS air is reaching the vadose zone near that point (Figure 2). At times longer than 15 to 20 minutes, tracer transport by diffusion and/or advection reduces the utility of the test. With co-located IAS and SVE wells, tracer reaching the water table will be drawn back towards the SVE well and appearance of the tracer at vadose zone monitoring points indicates that tracer reached the water table beyond that radial distance from the IAS well.

3.0 RESULTS AND DISCUSSION

Helium tracer tests have been conducted at a number of sites, most recently as part of a Department of Defense (DoD) multi-site air sparging evaluation project funded through ESTCP. Three of those IAS sites will be examined here. One site is located in a mildly stratified sand (Port Hueneme, CA [PH]), one is in a relatively homogeneous sandy gravel (Eielson AFB, AK [EAFB]), and one is in a stratified sand and clay aquifer (Hill AFB, UT [HAFB]). Two of the sites had co-located SVE systems and were evaluated as part of pilot tests (PH and EAFB). Air injection rates for those two sites were from 5 to 20 scfm and both sites had single well installations. The depths of injection at the first two sites were 2 to 3 m (6 to 10 feet) below the water table. The HAFB site had four IAS wells with co-located SVE wells. The injection rate was approximately 12.5 scfm per IAS well and the depth of injection was approximately 23 ft below the water table. System installations are described in more detail for PH in Bruce et al. (2000), and for EAFB and HAFB in Johnson et al. (2000).

3.1 Port Hueneme, CA

Two helium tracer tests were conducted at Port Hueneme, CA (IAS Site 2). The first used an IAS well with a screened interval at 4.4 to 6 m (18 to 20 feet) below ground surface (2.4 to 3 m below the water table, depending upon the season.). The air injection rate was 5 scfm and the co-located SVE system operated at 80 scfm. Figure 3a shows that only approximately 40% of the injected helium was recovered by the SVE system. Based on soil boring logs and flow versus pressure data, it was concluded that this occurred because air injection was beneath a lower-permeability layer at 17 to 18 feet. As a result of the incomplete recovery of the IAS air, the sparge well screen was relocated to a depth of 16 to 17 feet below ground surface (6 to 8 feet below the water table depending upon the season). The air injection rate for this test was 10 scfm

and the SVE system again operated at 80 scfm. In this case, helium recovery was nearly 100 percent (Figure 3b), indicating that the SVE system was capable of capturing essentially all of the IAS air.

Concurrent with startup of the recovery tests described above, tracer concentrations in the deep vadose zone were monitored at 12 locations approximately 0.5 m above the water table. A plan view of the site with the locations of the monitoring points and the co-located IAS and SVE wells is shown in Figure 4.

Figure 4a shows the deep vadose zone helium tracer distribution for air injection when the IAS well was at 4.4 to 6 m (18 to 20 ft) bgs. Based on the tracer appearance, essentially all of the injection air was entering the upper right-hand quadrant and some of the injection air appeared to be traveling beyond the monitoring network, which is consistent with the observed 40% recovery of tracer in the SVE off-gas. Both factors are a concern since (1) air distribution appears to be asymmetrical to the point that additional IAS wells may be needed to adequately sparge the entire site, and (2) more importantly, the SVE system is unable to capture all of the injected air.

Figure 4b shows the deep vadose zone tracer distribution for the 3.8 to 4.1 m (16 to 17 ft) IAS well depth. Once again, most of the injected air enters one quadrant. While this still represents a potential concern with regard to the positioning of additional wells to achieve complete coverage of the area, the SVE system is at least able to completely capture the injected air as demonstrated by the tracer recovery test. From this data, it generally would be concluded that an IAS well spacing of approximately 15 feet would be sufficient to obtain complete coverage. In this case, no tracer is detected at the monitoring points 30 feet from the sparge well; however, this data alone is not enough to determine if all of the air and tracer are appearing within the 30 ft radius around the sparge well. The tracer recovery test data would be needed to confirm that the SVE system was effective at capturing all of the IAS air if vapor migration is a concern at the site.

To further assess air distribution at the PH site, a sulfur hexafluoride (SF_6) tracer test was conducted (Johnson, 1996). Briefly, the test involves adding SF_6 to the IAS air at a known rate and measuring the concentration of SF_6 in the groundwater. The test can be used to estimate air/water mass transfer rates during sparging or it may simply be used to determine where air has and has not gone during sparging. The test was used in the latter mode here. Data from the two IAS well depths shown in Figure 5 indicate that in both cases, the air distribution in the groundwater was relatively localized and somewhat different than would have been anticipated from the deep vadose zone helium data. In particular, the SF_6 data do not show any air pathways

that would have carried the IAS air beyond monitoring points 9 and 10 (20 and 30 ft from the IAS well, respectively). This probably reflects the complex, erratic behavior of the air in saturated media and again points to the need for multiple lines of evidence for assessing IAS performance.

3.2 Eielson AFB, AK

A series of tests similar to those at Port Hueneme was conducted at Eielson AFB, Alaska. IAS was conducted sequentially in two wells, one at a depth of 6 feet below the water table, the other at 10 feet below the water table. Twelve deep-vadose zone monitoring points were distributed around the IAS wells at distances of 5,10, 20, and 30 feet. Air injection rates were 5 scfm in the shallow well and 10 scfm in the deep well. Four SVE wells were co-located with the IAS wells. The vadose zone at the site was quite fine-grained, and the maximum SVE rate that could be achieved without excessive upwelling of water was a combined total of 15 scfm.

Helium recovery tests were conducted at 5 scfm in the shallow well and 10 scfm in the deep well. In both cases, the tracer quickly appeared in the SVE wells and the tracer concentration rose to approximately 100% recovery (Figure 6). When helium injection was stopped, the concentration quickly dropped. These data suggest that most of the air is exiting the water table relatively near the injection well. To evaluate this, as in the previous case, at the beginning of the recovery test, tracer concentrations in the deep vadose zone were monitored. At this site, there were 12 vapor monitoring points, each at a depth of 6 feet (i.e., 2 feet above the water table). The deep vadose zone distribution data at the 5 scfm injection rate support this observation. No helium was observed at any of the deep vadose zone points indicating that all of the air came up within a 5 foot radius of the well (Figure 7a).

When air was injected at 10 scfm into the deeper well screen, helium was observed at one location 10 feet from the sparge wells (Figure 7b). As a consequence, it can be concluded that some of the air reaching the water table was from greater than 10 feet from the well.

As in the PH case, to further assess the distribution of air in the subsurface, an SF_6 air distribution test was conducted. The SF_6 was injected for approximately 12 hours and then samples were collected from each of the 12 groundwater monitoring points. The data in Figure 8 suggest that the IAS air was widespread at a distance of 10 feet from the IAS well, and was present in one monitoring point at 20 feet from the IAS well.

To better understand the reasons for the difference between the helium and SF_6 data, SF_6 pulsed tracer tests (Johnson et al., 2000) were conducted in the vadose zone to determine transport times to the SVE well. Basically, for each test a known volume of SF_6 (a few mL) was injected into a monitoring point and its arrival time at the SVE well monitored. Based on simple

geometric calculations, the time required for transport through the vadose zone to the SVE well can be calculated. Assuming that the thickness of the vadose zone is 8 feet, the distance from the SVE wells is 20 feet, the pumping rate is 15 scfm, and the air-filled porosity is 0.3, it should take about 200 minutes for the tracer to move to the SVE well. As the data in Figure 9 indicate, tracer injected at this distance arrived at the SVE will within approximately 50 minutes suggesting that there is preferential flow in the vadose zone. Since other data show the flow to be radially relatively symmetrical, and since the site is known to be overlain with finer-grained materials, the interpretation of these data are that vadose-zone air flow occurs primarily in the immediate vicinity of the water table. Since the vadose zone monitoring points are approximately 2 feet above the water table, and probably in the finer-grained materials, there may be bypassing of these points by the helium during the recovery test. These data once again point out the challenges associated with evaluating IAS at real-world sites, as well as the importance of using multiple lines of evidence for those evaluations.

3.3 Operable Unit (OU)-6, Hill AFB, UT

OU-6 is a stratified site where the aquifer is composed primarily of sands and silty sands. It is overlain by silt with beds of sand and clay. The interface between these two is near the current water table at approximately 105 feet below ground surface. A line of four sparge wells with co-located SVE wells was placed across a portion of a dissolved trichloroethene (TCE) plume which was exiting the base boundary (Radian International, 1995). In addition, nests of monitoring wells were distributed around the treatment zone. The locations of the wells are shown in Figure 10.

Under normal operation, the total IAS injection rate for the 4 wells was approximately 50 scfm and the extraction rate from the 8 SVE wells was about 175 scfm. A tracer recovery test was conducted at the site under steady sparging conditions by injecting helium into the IAS wells at a total rate of 0.55 scfm. The concentration in the air coming from the SVE system was measured as a function of time and after approximately 500 minutes of injection, a helium recovery rate of approximately 20% was measured (Figure 11).

During the test it was observed that air was flowing from a number of the shallow monitoring wells which were screened 5 to 10 feet below the water table. As a consequence, the air flow and helium concentrations from each of the wells were monitored during the test. In Figure 10 the upper number associated with each monitoring well is the total flow of air out of the well, the lower number is the flow rate of helium out of the well (i.e., helium concentration times

total flow rate). As can be seen, approximately 75% of the injected helium was flowing out of monitoring wells 7 and 8. From the data in Figures 10 and 11, it can be concluded that air is being trapped in an extensive pocket beneath the water table in the vicinity of the well screens for the shallow wells. This conclusion is supported by the pressure data reported by Johnson et al. (this issue).

4.0 CONCLUSIONS

If lateral migration of vapors from an IAS system poses a risk and an SVE system is installed to minimize that risk, then helium tracer tests are an important means of assessing the performance of the SVE system for recovery of IAS air. The ease and speed with which these tests can be conducted and interpreted makes them well suited for IAS pilot tests (even 1-day tests). The tests can also be conducted on systems that are already in operation. The tests can be easily repeated, which allows system parameters to be modified and the impact of those modifications to be assessed. In the absence of an SVE system (or with a co-located SVE system), the distribution of air reaching the water table can be estimated by observing the movement of helium out of the groundwater zone using vadose zone monitoring points placed just above the water table. These tests can provide important insight into air distribution, including the distances from the IAS well that the sparge air reaches and whether or not air flow is radially symmetrical around the well. However, as the cases presented here point out, the helium tracer tests are of greatest value when they are used in conjunction with other diagnostic tests.

5.0 REFERENCES

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Johnson, R. L.; R.R. Dupont and D.A. Graves, 1996, "Assessing UST Corrective Action Technologies - Diagnostic Evaluation of In situ SVE-Based System Performance.EPA/600/R-96/041, 164p.

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Radian Corporation, 1995, Interim IAS/SVE Test Technology Demonstration Report, Operable Unit 6, Hill Air Force Base, Utah, 25 September 1995.

Figure 1a. HELIUM TRACER TEST FOR ASSESSING IAS AIR RECOVERY

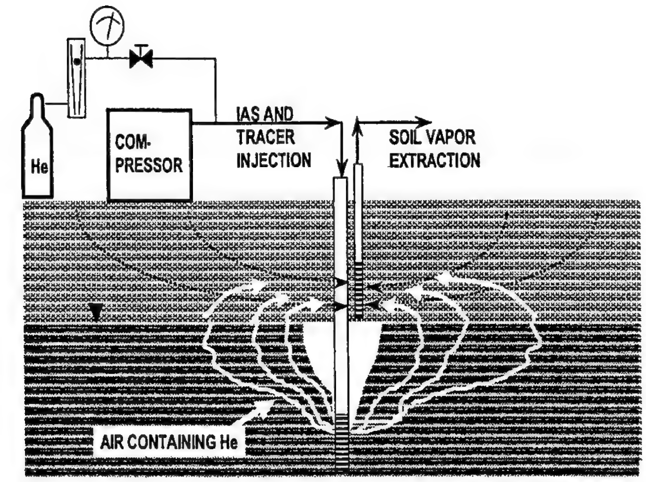


Figure 1b. HELIUM TRACER TEST FOR ASSESSING IAS AIR RECOVERY

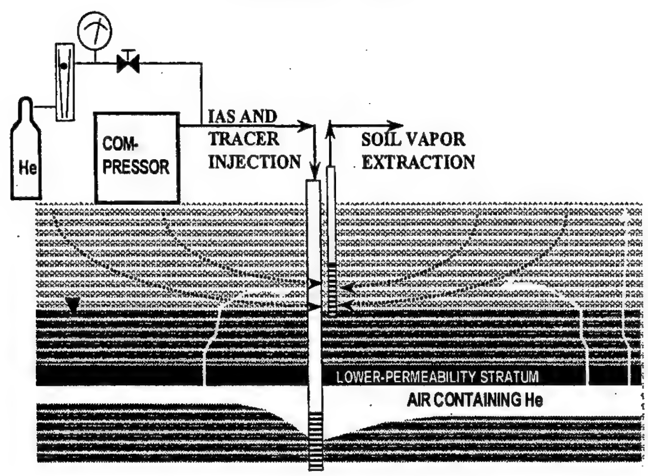


Figure 2.

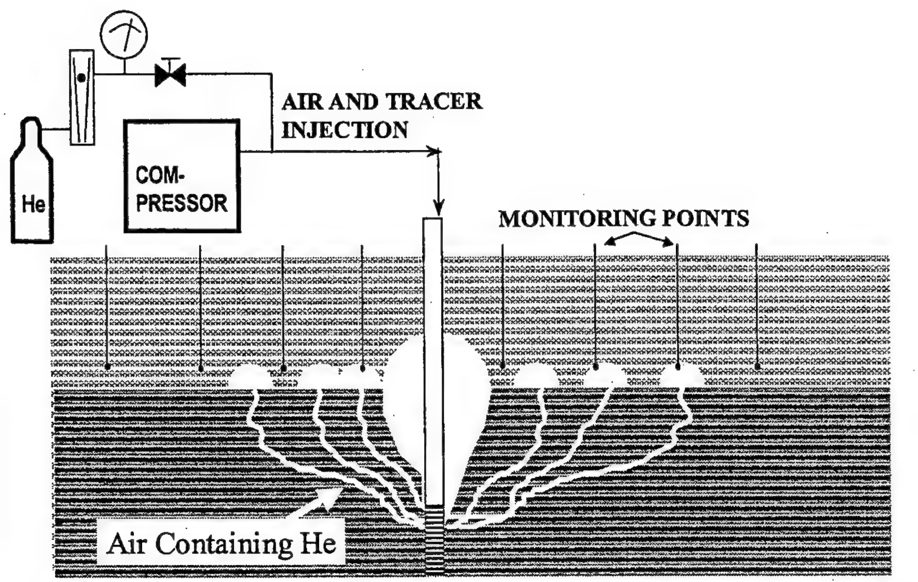
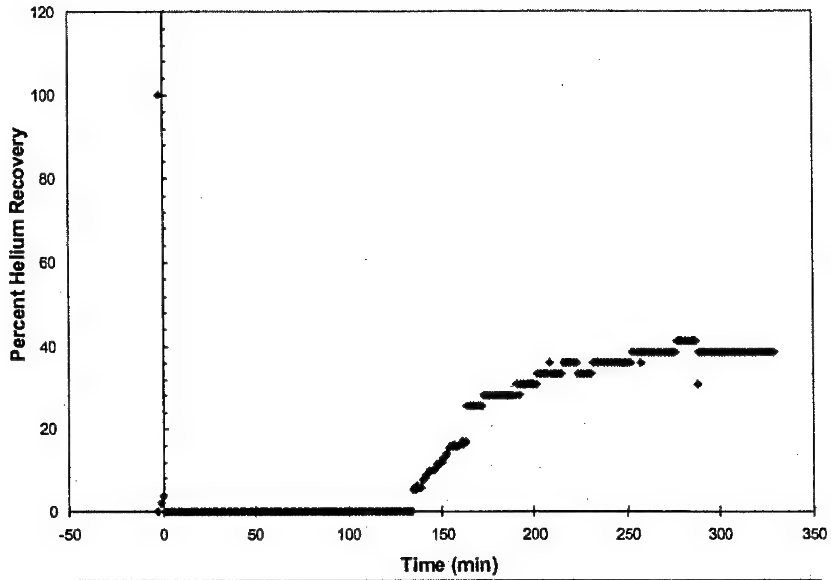

AIR AND TRACER
INJECTION
He
COM-
PRESSOR
MONITORING POINTS
Air Containing He

Figure 3a. Helium Recovery Test Site 2 970725



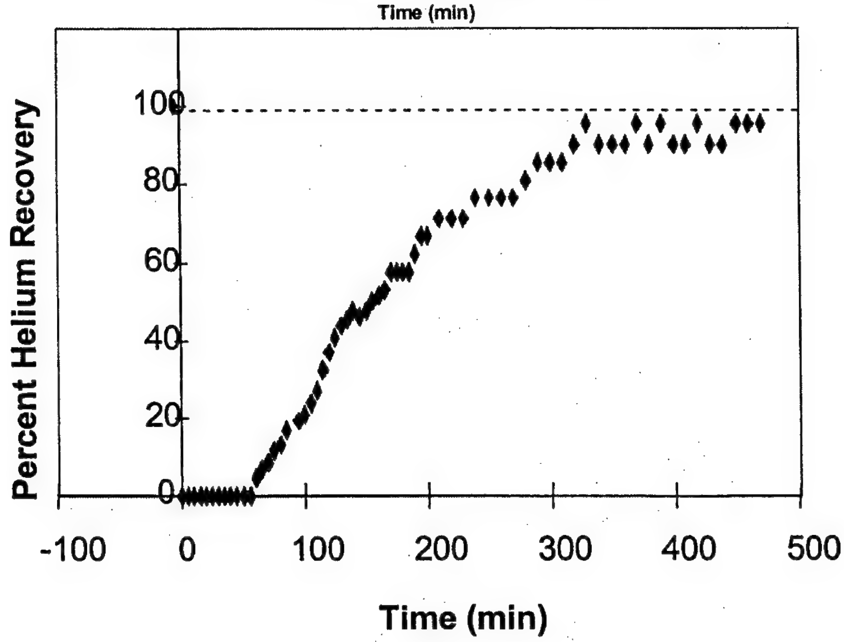
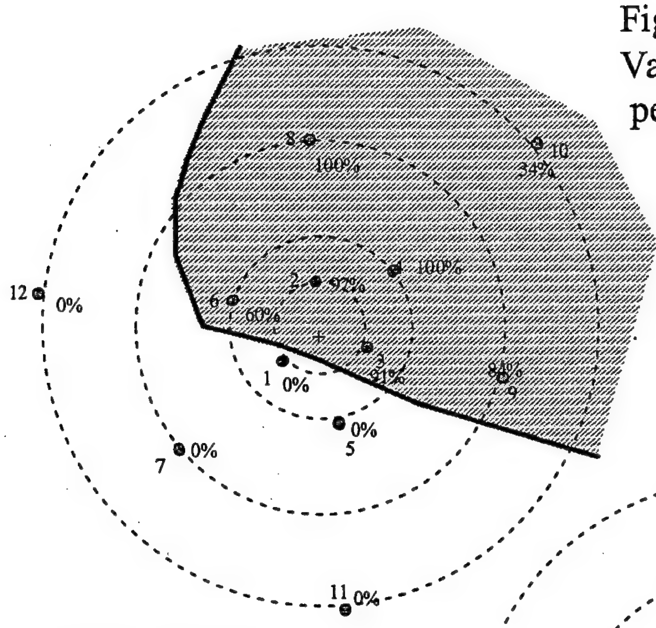
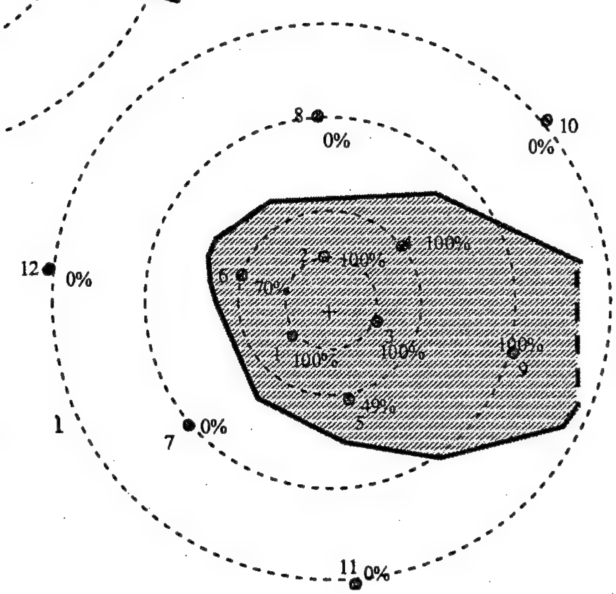


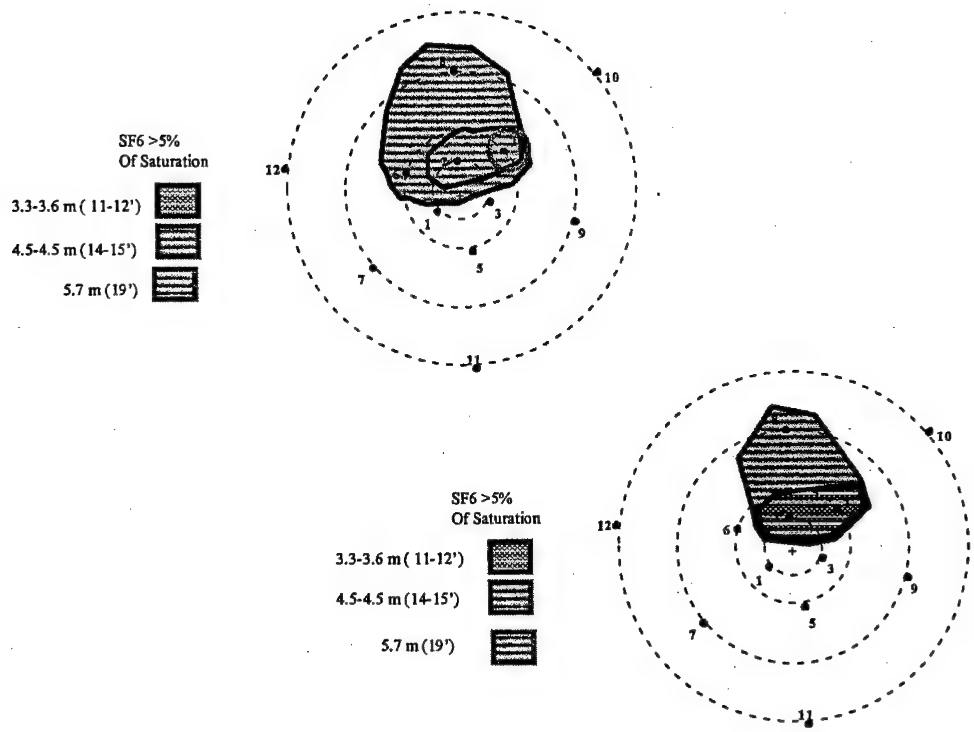
Figure 4. Helium in the Deep Vadose Zone - Site 2 (Values represent percent of helium injection concentration)



a) IAS injection at 5.5-6m (18-20 feet) at 5 scfm



b) IAS injection at 4.8-4.1 m (16-17 feet) at 10 scfm


SF6 >5%
Of Saturation
3.3-3.6 m (11-12')
4.5-4.5 m (14-15')
5.7 m (19')
10
12
1
3
5
7
9
11
SF6 >5%
Of Saturation
3.3-3.6 m (11-12')
4.5-4.5 m (14-15')
5.7 m (19')
10
12
6
1
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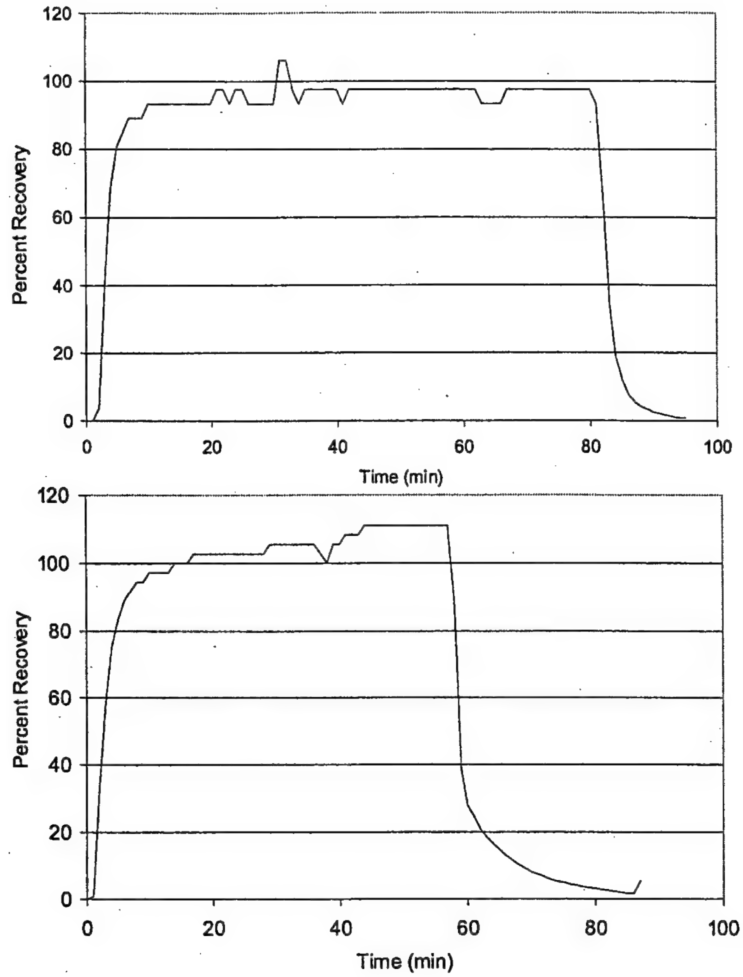
11

Figure 5.



120
100
80
60
40
20
0
Percent Recovery
0
20
40
60
80
100
Time (min)
120
100
80
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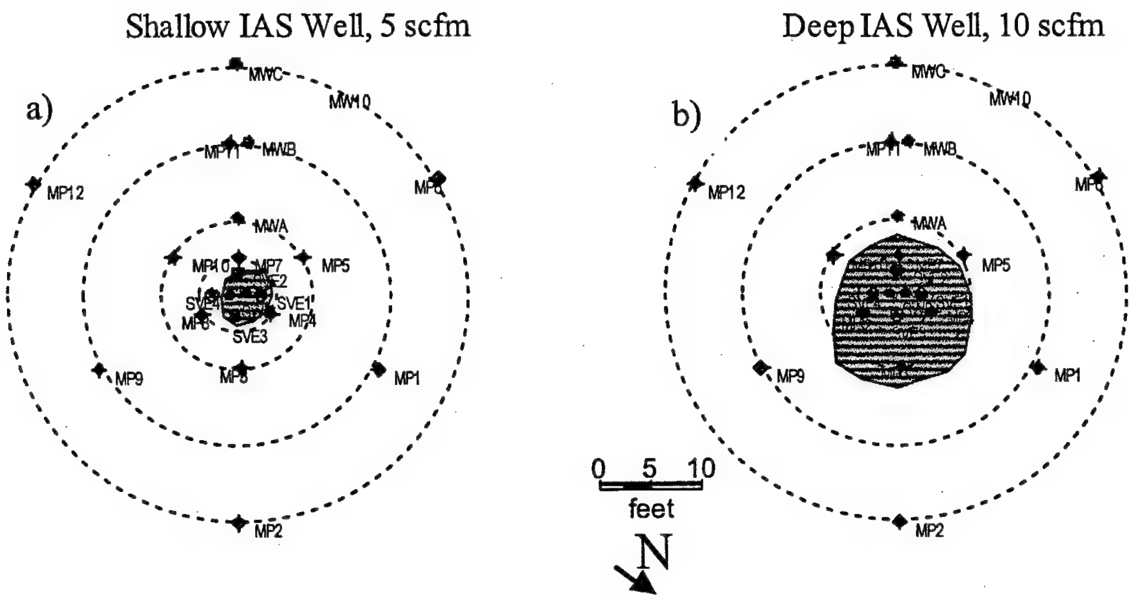
40
20
0
Percent Recovery
0
20
40
60
80
100
Time (min)

Figure 6.



Shallow IAS Well, 5 scfm
Deep IAS Well, 10 scfm
a)
b)
MWC
MW10
MP11
MWB
MP12
MWA
MP10
MP7
MP5
SVE1
SVE3
MP4
MP9
MP1
MP2
0 5 10
feet
N

Figure 7.

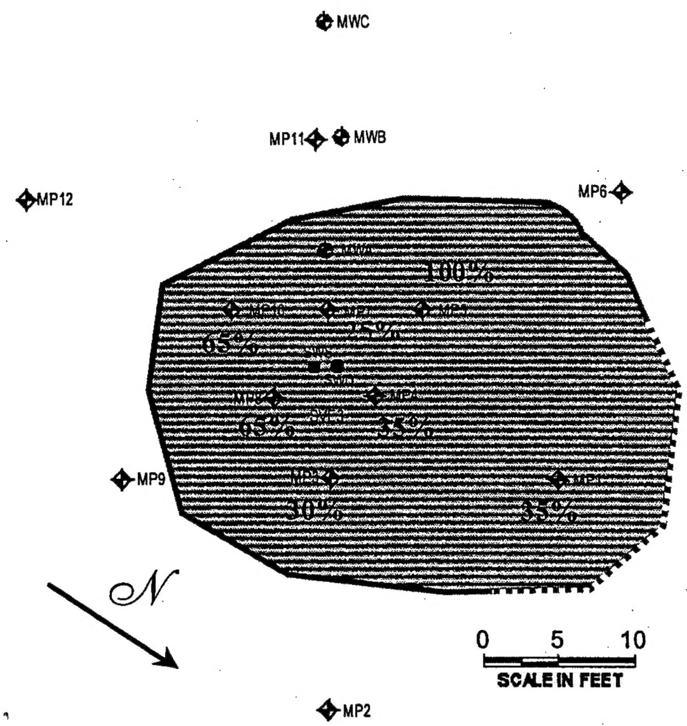

MWC
MP11
MWB
MP12
MP6
100%
65%
65%
35%
MP9
30%
35%
N
0
5
10
SCALE IN FEET
MP2

Figure 8

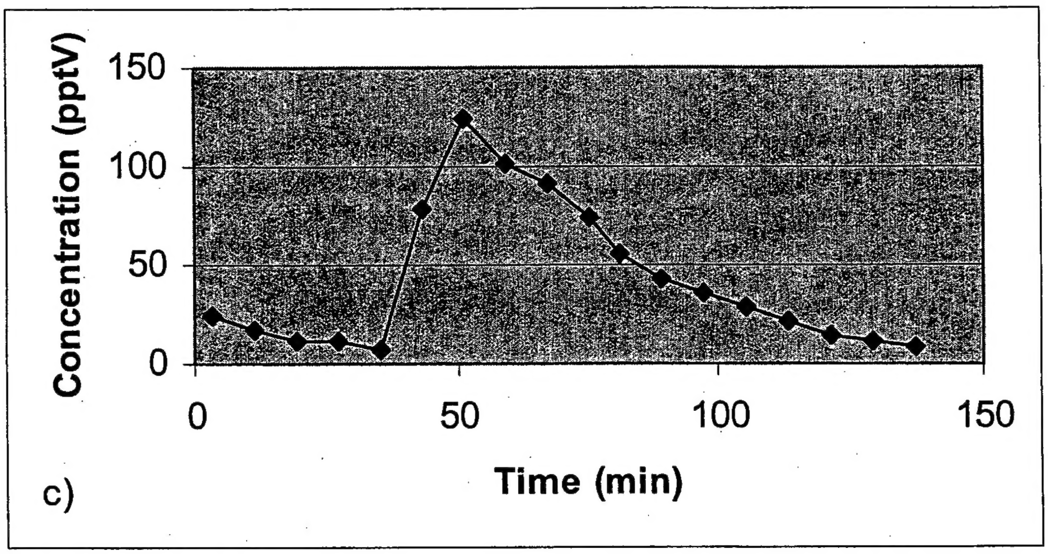


Figure 9.

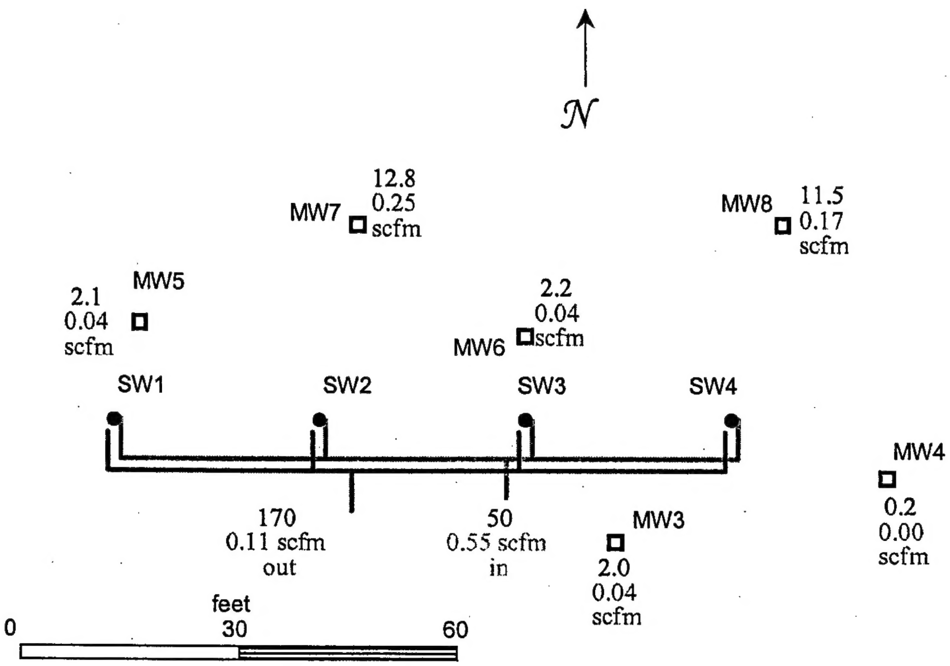
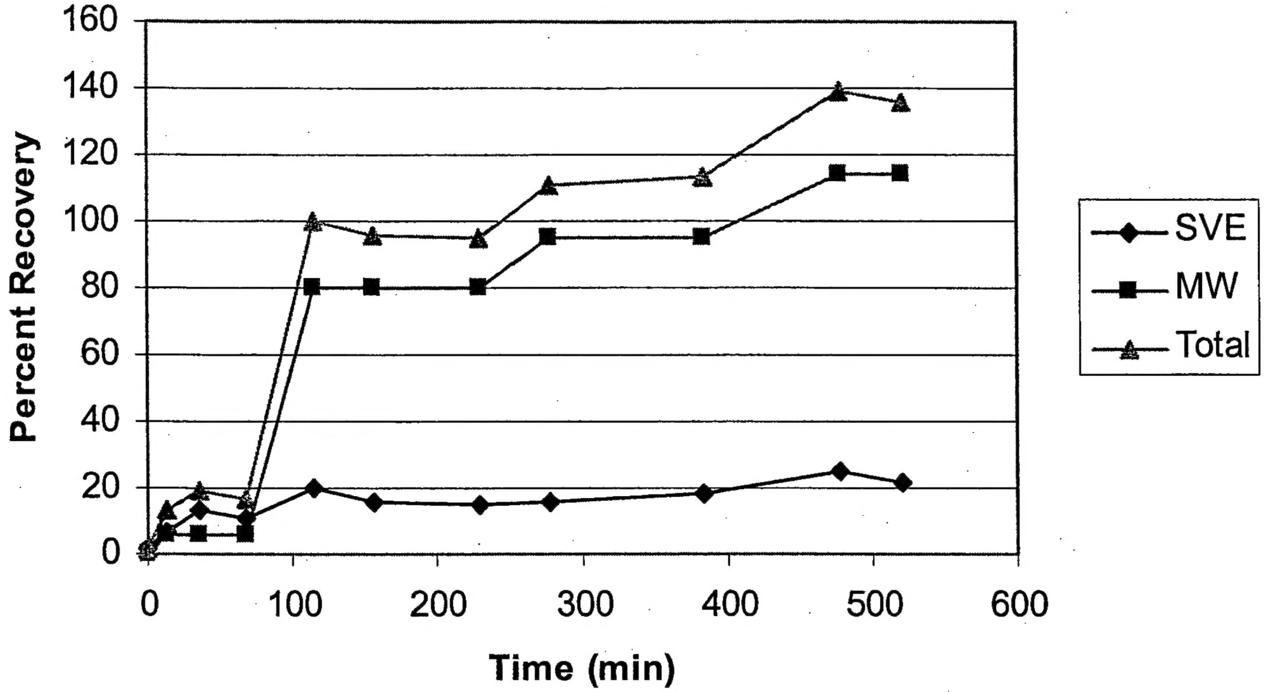

N
MW7
12.8
0.25
scfm
MW8
11.5
0.17
scfm
MW5
2.1
0.04
scfm
MW6
2.2
0.04
scfm
SW1
SW2
SW3
SW4
MW4
0.2
0.00
scfm
170
0.11 scfm
out
50
0.55 scfm
in
MW3
2.0
0.04
scfm
feet
0
30
60

Figure 10.



160
140
120
100
80
60
40
20
0
Percent Recovery
0
100
200
300
400
500
600
Time (min)
SVE
MW
Total

Figure 11